DYNAMICAL STUDIES IN HURRICANE INTENSITY CHANGE AND HURRICANE MOTION

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LONG TERM GOALS/OBJECTIVES

The long term goals and objectives of this research are to develop a physical understanding of tropical cyclone (TC) intensity change processes and the motion of a three-dimensional hurricane vortex. Towards these goals, this years work focused in three main areas: barotropic hurricane motion, the impact of convective asymmetries on TC intensity changes, and swirling boundary layers. The following pages summarize pertinent milestones in each area.

BAROTROPIC HURRICANE MOTION: MOTIVATION AND APPROACH

Although much research has focused on understanding the barotropic motion dynamics of idealized vortices in a quiescent environment on a beta plane, there is still disagreement about the long-time ($\geq$10 days) vortex speed and direction in a fluid possessing a finite equivalent depth. Willoughby (1995) found in his linear simulations that the vortex speed constantly accelerates without an asymptotic limit and attributed the acceleration to a normal mode of near-zero frequency which could not be identified by other researchers. If Willoughby is correct, then his work suggests that the motion of an intense vortex in equivalent barotropic dynamics is fundamentally different from predictions based on non-divergent or quasigeostrophic dynamics. We therefore think it is important to either validate or falsify the Willoughby paradigm before advancing into the three dimensional motion problem. This research thrust uses the asymmetric balance (AB) formulation (Shapiro and Montgomery, 1993) to investigate the long-term motion of a hurricane and evaluate the results of Willoughby.

Work Completed, Results And Impact

Using the AB formulation in an earth-based coordinate system on the beta plane, Montgomery et al. (1997) found that for a spectrum of vortices the drift speed predicted by the linear AB model asymptotes to a finite value. The evolution of the asymmetries in the beta plane experiments, including those of Willoughby (1995), were also found to be more accurately described as the symmetrization of outer-core gyres than the forcing of a normal mode of near-zero frequency. Together, these results refute the Willoughby paradigm of linear hurricane motion.

The linear AB model was extended to a nonlinear one so that wave-wave and wave-mean-flow interactions are included. Consistent with other works, asymptotic drift speeds are reduced from their linear values. Vortices develop an anticyclonic circulation in the vortex periphery and shed a Rossby-wave wake in their environment. Differences were found in vortex track, direction, and speed between our results and those of Willoughby (1994). These differences could be explained by axisymmetrization and energy/entrophy cascade (Fig. 1). The vortex track direction was found to be sensitive to azimuthal wavenumber truncation. It is concluded that for long-term integrations retention of asymmetries with at least azimuthal wavenumber 4 is necessary for accurate representation of the vortex track.

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Although the local Rossby number was not small, so that the fundamental assumption of the AB theory is not satisfied when wavenumbers > 1 are included, we are confident in the results. Recent calculations using a primitive equation model (Shapiro 1997) essentially replicate symmetrization experiments using the AB formulation (Möller and Montgomery 1997) where azimuthal wavenumber ≤ 4 are included.

CONVECTIVE ASYMMETRIES IN TC'S: MOTIVATION AND APPROACH

A new mechanism of vortex intensification by convectively forced vortex Rossby waves was proposed by Montgomery and Kallenbach (1997, henceforth MK). The thrust of this work is to further explore the Rossby wave intensification mechanism in hurricane-strength vortices. Here we use a barotropic shallow-water formulation where explicit convection is excluded. While much of the observed asymmetries are convective in nature, we focus on the horizontal advective dynamics. Convection is represented to the extent that the prescribed initial PV anomalies could be convectively forced.

Work Completed, Results and Impact:

Möller and Montgomery (1997) use a nonlinear semi-spectral shallow water AB model to examine the PV mixing/redistribution processes associated with finite amplitude vortex Rossby waves in hurricanes. The model is initialized with PV asymmetries and is integrated over a period of 3 days. During this time the asymmetries axisymmetrize and their kinematics and wave-mean-flow interaction are accurately characterized by the vortex Rossby-wave mechanics of MK. In case of a wavenumber 2 PV asymmetry initialization which was 20% of the basic-state PV we found an acceleration inside and a deceleration outside the RMW. The PV asymmetries circulate cyclonically around the vortex center and radiate outward. After 72 hours the asymmetries propagate further outwards and essentially disappear inside a radius of 150 km (Fig 2a). When the asymmetry was 40% of the basic-state PV we found in addition a wave-induced eigenmode which interacted with the vortex. In this case not all of the PV asymmetry is symmetrized away and after 72 hours a wavenumber 2 PV asymmetry remains in the center (Fig. 2b).

With respect to real hurricanes, one can imagine that convection creates asymmetries similar to the ones discussed above. The asymmetries are able to change the vortex, but the stronger asymmetry (40% of basic-state PV) changes the vortex insofar that the vortex becomes slightly unstable and is able to support a discrete eigenmode. The vortex could sustain the eigenmode, which then itself could interact with the convection and then feed back to the vortex. The dynamics of this convective feedback is beyond the scope of the present investigation and will be examined in a three-dimensional model (see transition).

SWIRLING BOUNDARY LAYERS: MOTIVATION AND APPROACH

As a foundation for upcoming work examining the life cycle of secondary eyewalls in hurricanes we have undertaken a study of the hurricane spin down problem. Specifically, we have examined the spin-down process for hurricane-like vortices subject to a quadratic drag law in the surface layer.

Work Completed, Results and Impact

As a basis for the numerical experiments presented, the time-dependent theory of Eliassen and Lystad (1977) was reviewed first. The theory was then tested with the assistance of an axisymmetric Navier-Stokes numerical model. Eliassen and Lystad's predictions were confirmed for weak vortices, but significant deviations from the theory arose when the vortex intensity was increased beyond tropical storm strength. At such swirl speeds the numerical simulations revealed a contracting radius of maximum tangential wind and a spin-up of a ring of vorticity just inside the radius of maximum tangential wind within the boundary layer before the ultimate spin-down of the vortex. The source of the spin-up was identified from an analysis of the vertical vorticity budget. The vorticity ring satisfies the necessary condition for barotropic instability and a simple estimate of the instability growth rate suggests that such rings are a favorable environment for the formation of destructive mesovortices near and within the hurricane eyewall. The details of this research are documented in Yang (1997). An investigation of the intensity change that accompanies the rearrangement of such unstable vorticity rings in the context of nondivergent dynamics has been carried out by Schubert et al. (1997).

Transitions

The work of Möller and Montgomery (1997) is being extended to three dimensions. The prognostic fully nonlinear model will be used to examine the effect of convectively-induced disturbances on the evolution of a hurricane-like vortex. This investigation will generalize that of Montgomery and Enagonio (1997), who studied tropical cyclogenesis using a quasigeostrophic balance model. The results of Yang (1997) will be written up for formal publication. A more complete stability analysis and three-dimensional lifecycle study of the frictionally and convectively generated vorticity rings including both radial advection and vertical diffusion will also be carried out in order to estimate the true extent of vorticity mixing near the hurricane eyewall and the inner-core intensity changes that accompany it. The results of this research will be used to better predict TC intensity change events which are currently forecast by operational models with little or no skill.

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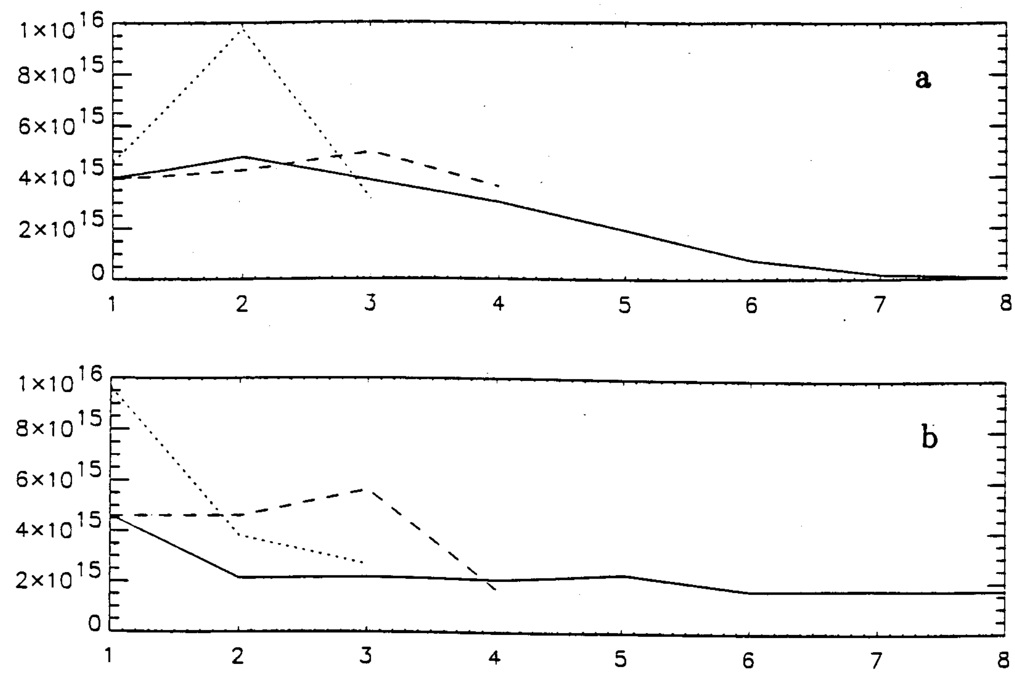

Figure 1. Area–integrated energy (ordinate) as a function of wavenumber (abscissa) for wavenumber truncation 3 (dotted line), 4 (dashed line), and 8 (solid line) after (a.) 4 days and (b.) 7 days. The wavenumber–1 dominates after 7 days for wavenumber truncation at 3, whereas for the higher wavenumber truncation the energy is more distributed to the higher wavenumbers. It is obvious that in the case of the wavenumber–3 truncation the wavenumber–1 energy is too large and seems to be "trapped" in wavenumber–1, which has an influence on the track.

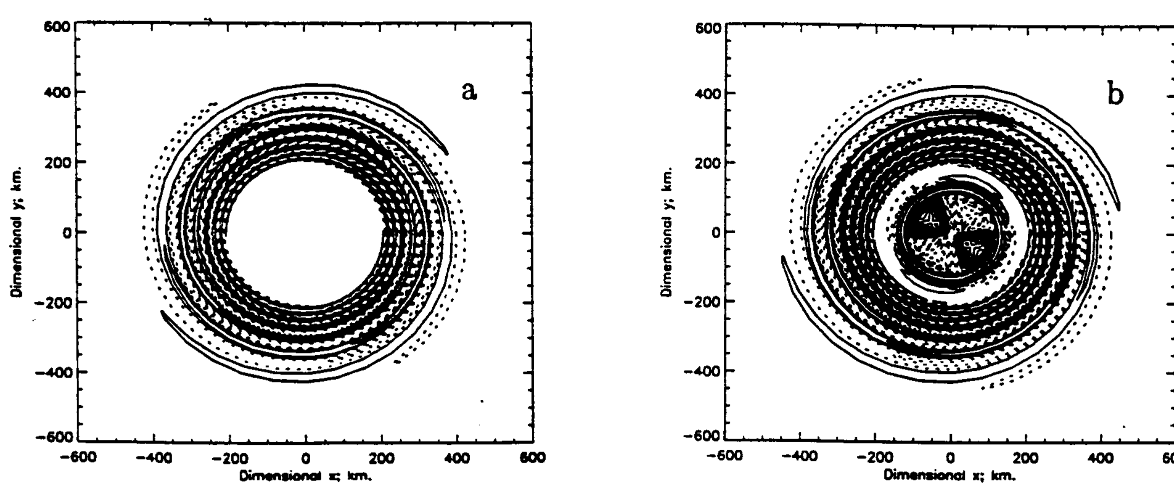

Figure 2. Horiziontal cross–section of the wavenumbe–2 PV asymmetry after 72 h. (a.) initially 20% of $\bar{q}$; Contour interval $1 \times 10^{-11} sm^{-2}$. (b.) initially 40% of $\bar{q}$; contour interval $2 \times 10^{-11} sm^{-2}$. In (a.) the asymmetries are symmetrized, whereas in (b.) a wavenumber–2 normal mode stays in the center.